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SURVIVABLE FLIGHT CONTROL SYSTEM DEVELOPMENT PROGRAM

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TECHNICAL MEMO FDC/ADPO-TM-70-1

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AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

SURVIVABLE FLIGHT CONTROL SYSTEM DEVELOPMENT PROGRAM

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Air Force Flight Dynamics Laboratory, McDonnell Aircraft Company
January 1970

On 7 July 1969, the Air Force Flight Dynamics Laboratory contracted with McDonnell Aircraft Company of St. Louis for a Survivable Flight Control System (SFCS) development program. This three-year, $16.5 million effort will develop and flight demonstrate technology that will significantly reduce the flight control system vulnerability of future aircraft to ground and air fire power. This paper is a resume of the SFCS program background, philosophy, plans and schedules.

The SFCS Program is based on the principle of dispersed redundant control elements providing improved control performance and a very stable weapons delivery platform. It combines fly-by-wire controls and integrated hydraulic servo-actuator packages to achieve a significant increase in flight control system survivability. Fly-by-wire decreases vulnerability of the control linkage from the pilot's control stick to the surface actuators through redundant dispersed electrical channels. The integrated servo-actuator packages decrease the vulnerability of power supplied to the actuators through redundancy and hardening. The full potential of such a survivable control system would be realized from aircraft employed in environments of hostile small arms fire, shrapnel, flak or projectiles of any size less than that which would destroy the integrity of the airframe structure.

The SFCS flight demonstrations will be backed up by a wealth of criteria, reliability, and applications studies that will provide a complete technology data package for developers of aircraft such as the B-1A, V/STOL fighter, LIT, AX, and SST. Due to the time frame, only a limited amount of technology will be available for the first models of the F-14 and F-15.

DEFINITIONS

Fly-by-Wire

Fly-by-wire is a closed-loop feedback control system which makes aircraft motion, rather than surface position, the controlled variable. The mechanical linkages between the pilot's stick and the control surface actuators are replaced by multiple physically dispersed electrical signal wires. The conventional center stick with its large motion envelope can be replaced by a small limited-motion sidestick with built-in armrest. The complex and troublesome feel system can be replaced by linear springs.

Integrated Actuator Package (IAP)

The integrated hydraulic servo-actuator package is a control surface hydraulic power actuator which has multiple electric motor driven hydraulic supplies internal to the package and, when used in a fly-by-wire system, receives power and control signals electrically. Aircraft survivability is increased since actuation of the primary flight control surfaces is not dependent on a maze of vulnerable central-system hydraulic plumbing.

Simplex IAP is a unit consisting of a dual-tandem actuator driven, under normal conditions, by the aircraft's central hydraulics systems. However, it also has a built-in motor, pump and reservoir (plus required failure sensors and valving) for emergency use. An F-4 Simplex stabilator (pitch axis) actuator built by LTV Electrosystems (Fig 1) will be flight tested in Phase I of the SFCS Program. Upon failure or battle loss of both primary central hydraulic systems, the built-in emergency system would provide get-home and land capability.

Duplex IAP is an actuator package which is completely independent of the aircraft's central hydraulic systems and their exposed plumbing. It has two independent motor-pump-reservoir units powering either a dual-tandem or a four-barrel ram (Fig 2). The two existing Duplex designs built by (General Electric and LTV Electrosystems) are sized as F-4 stabilator actuators, but are not flightworthy units. Either half of the Duplex unit is capable of providing full rated hinge moment and surface rate.

Triplex IAP is a full-time self-contained actuator similar to the Duplex, but with three independent motor-pump-reservoir units. At present, the Triplex IAP exists only as a paper design.

Survivability

Survivability is the capability of a system to withstand a manmade hostile environment without suffering abortive impairment of its ability to accomplish its designated mission. (AFR 80-38)

Vulnerability

Vulnerability is the characteristic of a system which causes it to suffer a finite degradation in the capability to perform its designated mission (s) as a result of having been subjected to a certain level of effects in a hostile environment. (AFR 80-38)

PROGRAM OBJECTIVE

The objective of the Survivable Flight Control System Program is to establish the technology base for, and flight demonstrate the feasibility of, a flight control system for future military aircraft that is significantly less vulnerable and more survivable than present day systems.

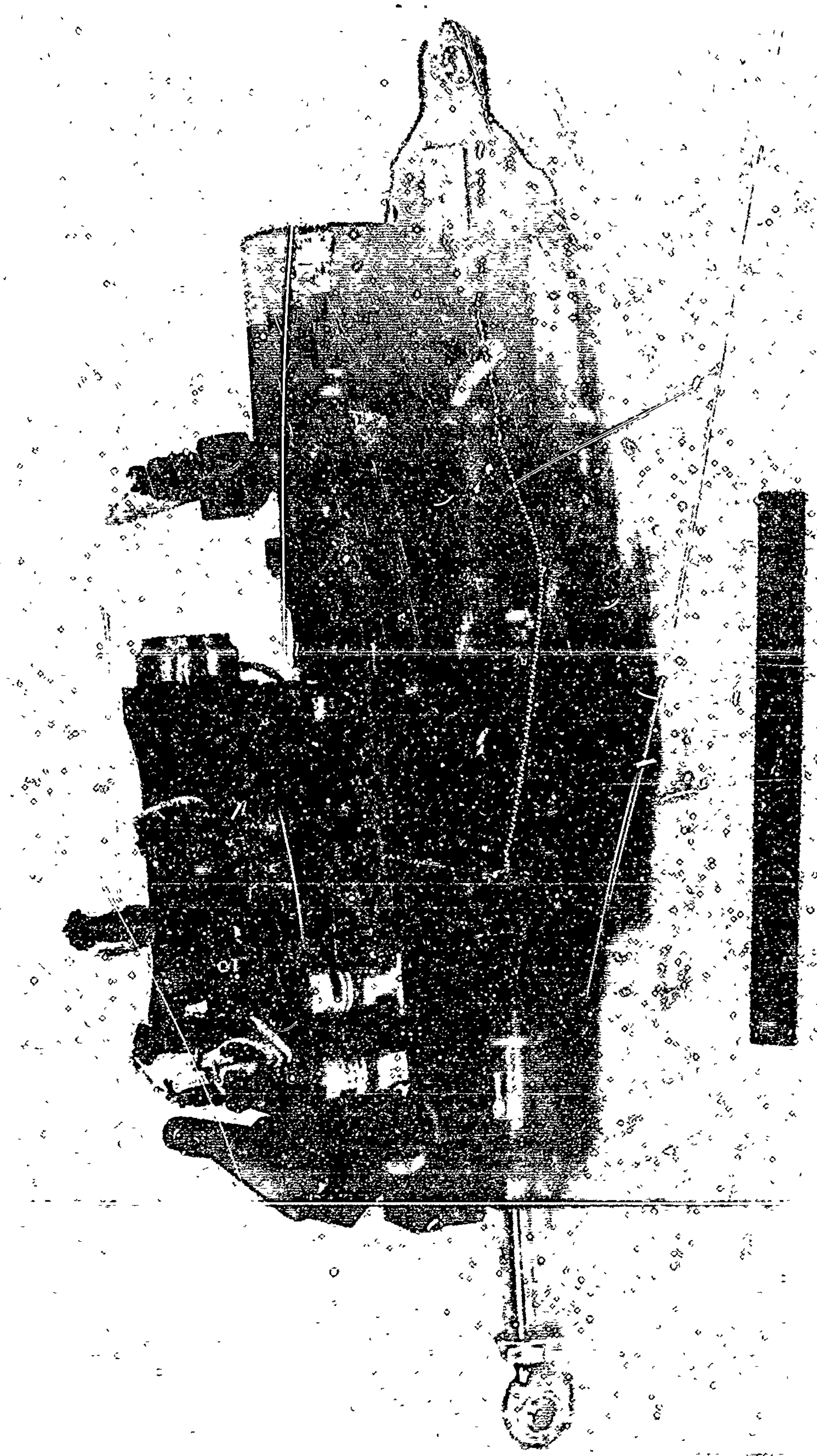


Figure 1 - SIMPLEX INTEGRATED ACTUATOR PACKAGE FOR SFCS FLIGHT TEST

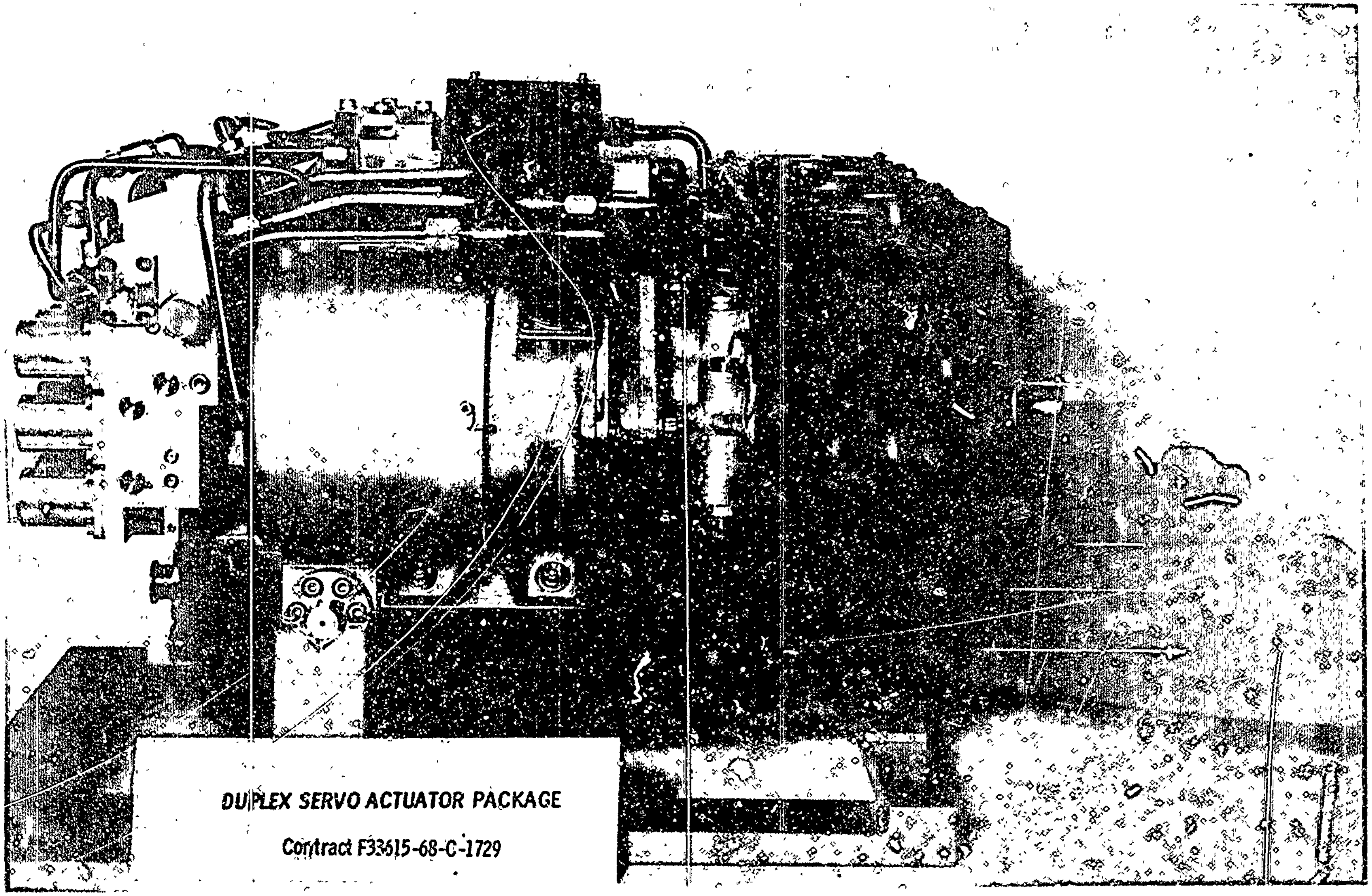


Figure 2 - F-4 STABILATOR DUPLEX INTEGRATED ACTUATOR PACKAGE

Simplex IAP

The Simplex IAP will be flight tested early in 1970 to establish confidence in this technique for providing emergency hydraulic get-home and land capability. The Simplex principle can then be considered for use in the F-15. (Simplex development was partially funded by the F-15 SPO.) The package shown in Fig 1 will not be used by the F-15 since size and power requirements are aircraft peculiar. However, this unit could be applied to the F-4 aircraft on a retrofit and/or new production basis.

Fly-by-Wire (FBW)

A quadruply redundant fly-by-wire system will be flown and demonstrated to interested agencies before the integrated actuator packages are installed in the test aircraft. This phased approach reduces development risks, and provides the earliest possible availability of a flight-proven fly-by-wire system for use in the B-1A, LIT, SST, AX, F-15X, F-14X, and V/STOL fighter.

Control Performance

In addition to the combat survivability improvement gained by redundancy, dispersion, reduction in exposed hydraulic plumbing, and hardening, a significant improvement in overall control system performance (precision tracking and weapon delivery, platform stability, and maneuverability) will result as an inherent characteristic of fly-by-wire systems. A survivability gain is realized through improved control performance because:

a. Improved weapon delivery minimizes the number of passes to be made on a target, thus minimizing exposure to hostile environment;

b. Greater weapon release ranges from higher altitudes reduce aircraft losses due to decrease in density of ground-to-air fire power.

c. Improved platform stability, handling and maneuverability result in effective evasive action during air combat.

Redundant Integrated Actuator Package

The improved control performance of the fly-by-wire system and the emergency capability of the Simplex IAP could be combined to provide a measureable improvement in flight control survivability. However, a truly survivable system requires use of redundant IAP's which are independent of central hydraulic systems and their exposed plumbing. In future programs, there may be a need for Duplex, Triplex, and possibly Quadruplex or full-time Simplex units. The exact degree of redundancy to be used on a given surface will depend on its criticality, and the number of alternate surfaces available to control the aircraft axis in question.

Objective Summary

The objective of the Survivable Flight Control System development program is vividly summarized in Figs 3 thru 5. Fig 3 shows the present F-4 mechanical flight control system. Fig 4 shows the dual primary and utility hydraulic systems of the F-4. Together these figures show a mass of extremely vulnerable hardware, with many single failure points. Fig 5 shows the F-4 SFCS with dispersed redundant electrical controls, and redundant integrated actuator packages. A new aircraft, designed for an SFCS, could improve survivability even further by providing multiple control surfaces in each axis.

The result of this program will be:

a. Establishment of a broader experience base in fly-by-wire and integrated actuator packages.

b. Demonstration of the advantages of these techniques in terms of survivability, reliability, and performance.

c. Assessment of the tradeoffs in such areas as weight, maintenance, and costs.

d. Documentation of this knowledge in terms of derived design, performance, reliability, testing requirements, and application criteria for use in acquisition of future weapon systems.

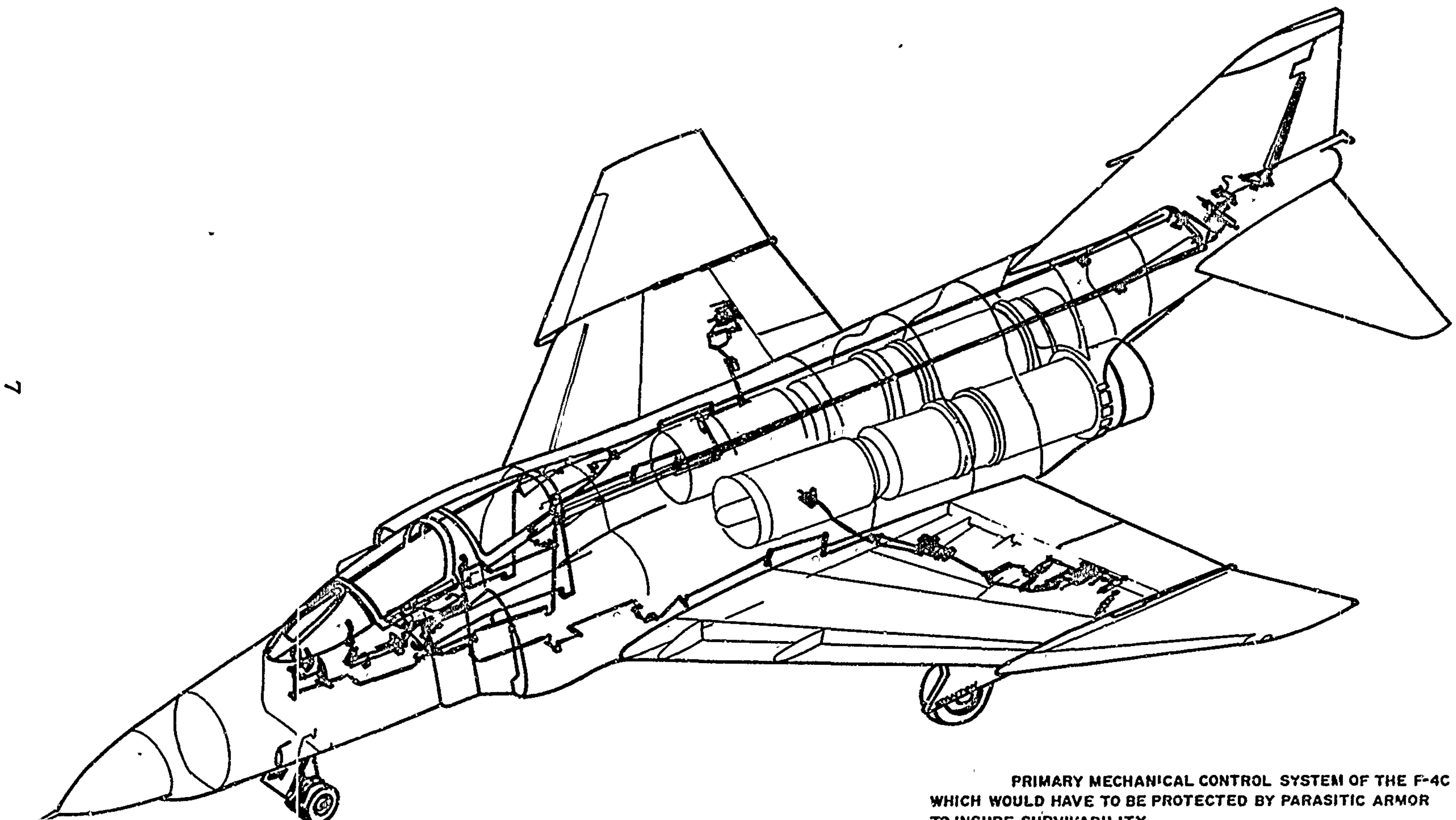
e. Formulation of solutions to associated engineering and psychological problems.

PROGRAM GENESIS

Combat experience in Southeast Asia indicates certain shortcomings in the ability of current USAF aircraft to survive intense ground fire. One of the major contributors to this vulnerability is the aircraft's flight control system which is responsible for a large percentage of the combat losses. Parasitic armor cannot be added to the aircraft structure to reduce this vulnerability without seriously reducing the performance of the aircraft.

The concept of combining fly-by-wire flight controls with integrated actuator packages to produce a survivable flight control system was developed at the Air Force Flight Dynamics Laboratory. The first presentation of the SFCS concept was made to Hq USAF on 7 July 1967. In August, further presentations were made to the SAC, TAC, ADC, and Aircraft Survivability Panels at Hq USAF. Approval of the original advanced development program plan was received from Hq USAF in AFRDDE message 122109Z, January 1968.

During 1968, studies were conducted to determine the most suitable test aircraft and define the major requirements of a survivable flight



PRIMARY MECHANICAL CONTROL SYSTEM OF THE F-4C WHICH WOULD HAVE TO BE PROTECTED BY PARASITIC ARMOR TO INSURE SURVIVABILITY.

Figure 3 - F-4 MECHANICAL FLIGHT CONTROLS

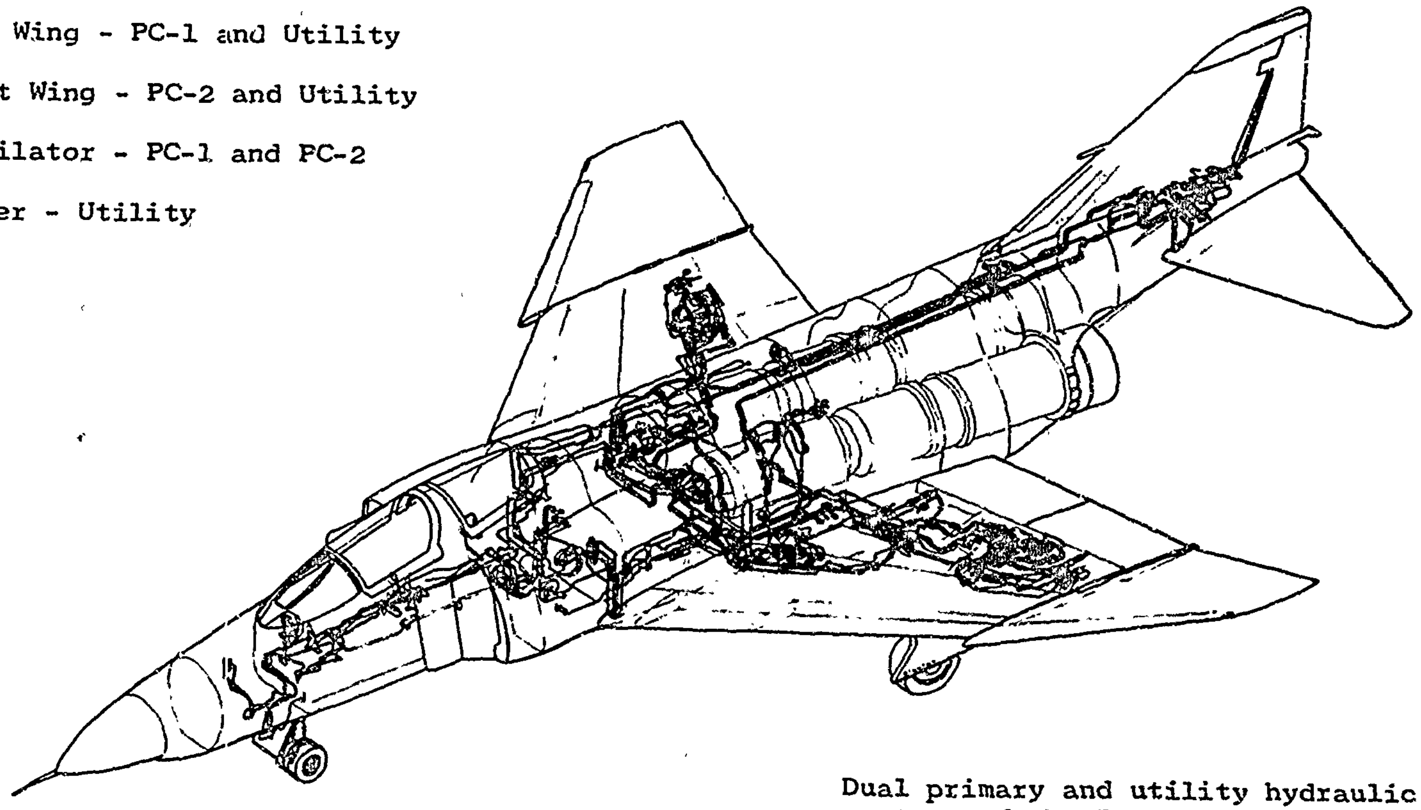
Hydraulic System Usage

Left Wing - PC-1 and Utility

Right Wing - PC-2 and Utility

Stabilator - PC-1 and PC-2

Rudder - Utility



Dual primary and utility hydraulic systems of the F-4 which would have to be protected by parasitic armor to reduce vulnerability.

Figure 4 - F-4 Hydraulic Systems

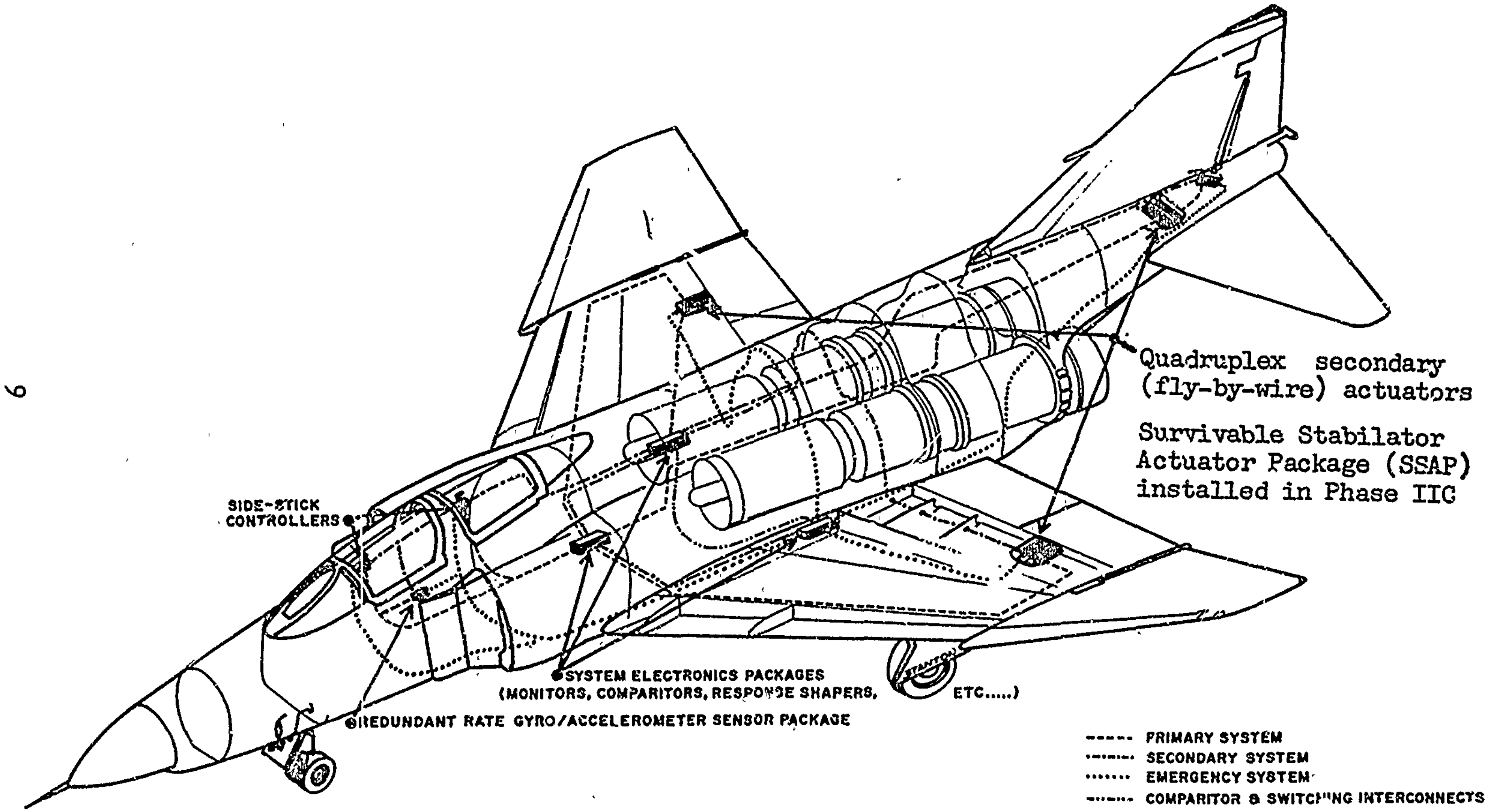


Figure 5 - F-4 SURVIVABLE FLIGHT CONTROL SYSTEM

control system. Aeronautical Systems Division (Air Force Systems Command), the major commands, the Federal Aviation Administration, and other agencies coordinated on the advanced development program plan, suggesting changes and additions to the SFCS program. Taken together, the studies and coordinations showed that mere flight demonstration of electrical flight controls and integrated actuator packages would not insure their use on future aircraft. Such radical departures from existing systems required in-depth studies to develop design, control, and flying qualities criteria, establish reliability, cost, and maintainability data, define applications, etc. A decision was made to flight qualify the Simplex integrated actuator package (IAP) then being built under exploratory development. The Simplex IAP flight test became Phase I of the SFCS Program. Thus, the resulting Statement of Work called for a much more extensive and ambitious program than originally proposed.

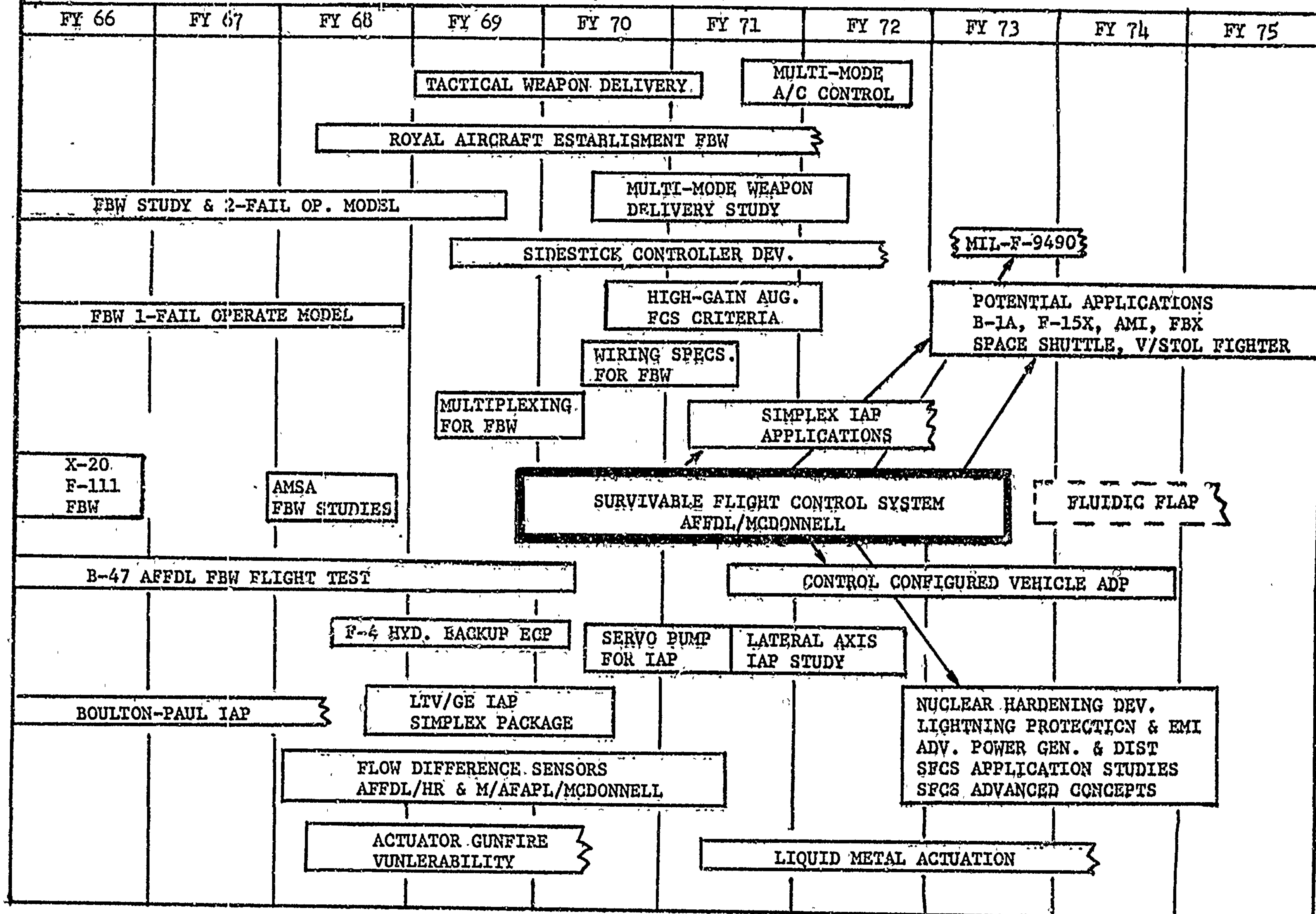
Several studies, including those under AMSA Task S-14c, selected the F-4 as the best flight test aircraft. A decision was made to contract with McDonnell Aircraft, builder of the F-4, for design, integration, and flight testing of the SFCS, and the associated studies. The redundant fly-by-wire electronics set, secondary actuators, and the integrated actuator packages (totaling 25 to 30% of the program cost) will be purchased by McDonnell under competitive subcontracts.

The McDonnell proposals were received in February of 1969. The next five months were spent in proposal evaluations, technical and cost negotiations, and gaining approval of the additional funds required. The funding problem was caused by the increased program scope noted above, plus underestimation by the Air Force of the original program costs. Final procurement approval authority was received in June 1969, and a letter contract with McDonnell Aircraft Company was signed on 7 July 1969.

RELATED AIR FORCE PROGRAMS

Several past and current exploratory development programs carried out by the Air Force Flight Dynamics Laboratory are directly related to the SFCS Program, See Fig 6. The benefits to be gained from the results of such programs as TWeaD (Tactical Weapon Delivery), LAMS (Load Alleviation and Mode Stabilization), Optimal Automatic Terrain Following, and DLC (Direct Lift Control) can all be more readily accrued by building upon a basic fly-by-wire flight control system. In fact, load alleviation, gust alleviation, and complexly-coupled control systems (such as those in VTOL aircraft and manned lifting re-entry vehicles) rely on motion feedbacks and therefore require fly-by-wire to realize their full potential without the compromises associated with mechanical systems. Thus, while this program directly provides a survivable flight control system for tactical aircraft, the technology developed will also apply to bomber, VTOL, lifting re-entry, reuseable launch vehicles, and many other vehicle classes as well.

Figure 6 - PROGRAMS RELATED TO THE SFCS EFFORT



THE QUADRUPLE REDUNDANCY APPROACH

The decision on the degree of redundancy to design into the system is influenced by two factors: First, the reliability required, and second, the failure-mode philosophy, both of which are dependent on vehicle mission. AF Flight Dynamics Laboratory studies to date have indicated that for advanced military or commercial aircraft the most acceptable degree of redundancy would be one which would provide a two-fail/operate capability. This is ordinarily acquired through quadruple redundancy and such a system would accept two like failures with little or no system performance degradation. On a third similar failure, the system goes to a neutral (soft) or preselected trim position. In this event, the pilot and/or flight engineer may have the option of bypassing each logic section and positively selecting each functional module throughout the control system. This would permit the crew, after three like failures, to make full use of any system capabilities which might remain. A module which failed to produce acceptable performance for normal operation might thus be successfully used to get the aircraft home.

SFCS DEVELOPMENT APPROACH

This program is divided into four parts, as illustrated in Fig 7. Phase I is a flight demonstration of the Simplex IAP which provides a backup get-home-and-land capability in the event the two primary aircraft hydraulic systems are lost. Phase IIA flight demonstrates a fly-by-wire flight control system with the mechanical system disengaged, but available for emergency use in the pitch and yaw axes. Phase IIB removes the mechanical backup to demonstrate confidence in a pure fly-by-wire electrical system. Phase IIC flight demonstrates a Duplex integrated actuator package in the longitudinal axis in conjunction with the fly-by-wire system.

The fly-by-wire system will employ high-gain feedback loops, self-adaptive control, micro-electronic integrated circuits, sidestick controllers, vernier control for precise weapons delivery, C* motion mechanization for longitudinal control, selectable neutral speed stability, reliability analyses, and lightweight motion sensors. The design will be confirmed by a six-degree-of-freedom simulation of the test aircraft and the proposed control system. As hardware components become available, they will be tied into the simulation in lieu of their computer-simulated counterparts. Simulations will continue through ground checkout and flight test of the system to serve as a basis for data correlation. Hardware items will also be tested on the "iron bird" control system mockup. The cockpits will be modified by the installation of sidestick controllers. Auxiliary A.C. and D.C. power sources are to be added as required to provide sufficient levels of redundancy for two-fail/operate capability. A hydraulically driven electric generator will be added to provide aircraft flight control capability under engine-out conditions. Studies show that a wind-milling engine will provide enough power through such a generator to fly the aircraft while engine restart is attempted. The primary

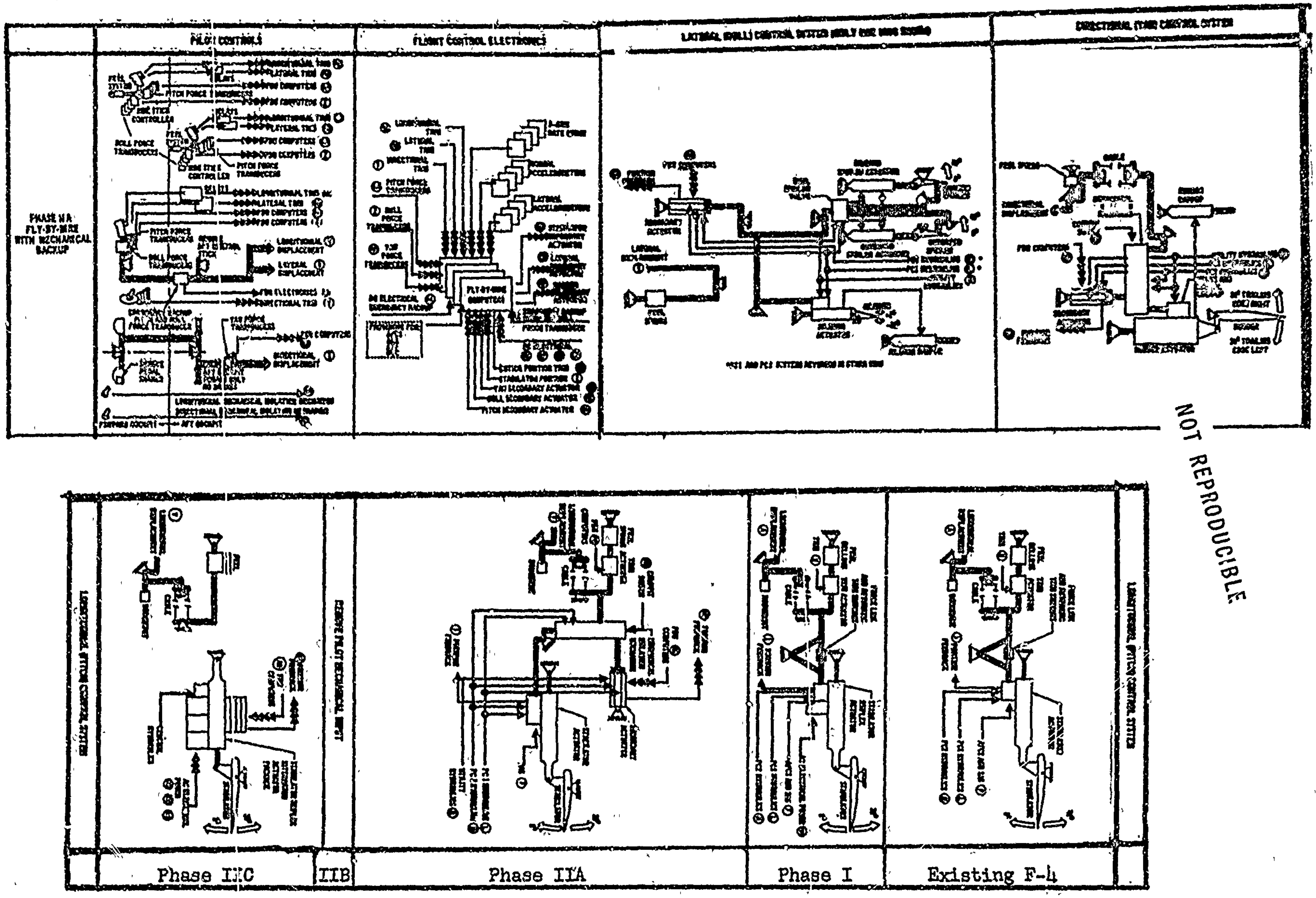


Figure 7 - SURVIVABLE FLIGHT CONTROL SYSTEM DEVELOPMENT APPROACH

electrical power sources for the fly-by-wire flight control system and the integrated servo actuator packages must be at least as reliable as the flight control system itself.

Flight tests will be conducted to optimize, evaluate, and demonstrate the SFCS system performance and handling qualities. Finally, the system will be flight demonstrated in mission modes applicable to the F-4 test aircraft (e.g., weapon delivery, aerial combat, high-speed low-altitude dash, etc.). Demonstration flights will also be conducted for USAF, Army, Navy, and commercial pilots. Data from the flight tests will be processed and correlated with ground checkout and simulation data continuously throughout the program.

PHASE I - SIMPLEX INTEGRATED ACTUATOR PACKAGE FLIGHT TEST

Phase I of the SFCS Program consists of the installation and flight testing of a Simplex package in the longitudinal axis of the F-4. The objectives of this phase are to:

* Demonstrate feasibility and survivability

* Form a confidence base

* Provide design, performance, reliability, maintainability, and test requirements

* Provide a proven actuator technique for F-15 consideration

A Simplex IAP built by LTV Electrosystems was qualified for flight in accordance with the Air Force Flight Dynamics Laboratory Simplex Servo Package Specification, F-4 Stabilator Control as revised 18 April 1969.

The Phase I work includes testing of the Simplex package on the "iron bird" control system mockup, and single point failure, maintainability and survivability analyses. Installation of the Simplex package requires modification of the aircraft structural attachment points, and the hydraulic and electrical systems. Approximately ten test flights are planned to assess Simplex performance, reliability, switching transients, etc.

A successful Simplex flight test, coupled with the comprehensive flight qualification tests referred to above, will provide an immediately available proven technique for increasing the survivability of new production aircraft such as the F-14 and F-15, or inventory aircraft through retrofit. As a bonus, the F-4 stabilator Simplex is a completely new design whose performance in normal operation could be superior to that of the standard F-4 actuator, whose basic design is rather old.

PHASE II - SURVIVABLE FLIGHT CONTROL SYSTEM

Phase II of the SFCS Program is intended to design, develop and flight demonstrate a Survivable Flight Control System consisting of a fly-by-wire control system and integrated actuator packages. The objectives of this phase are to:

* Establish a broader experience base in fly-by-wire and integrated actuator package techniques

* Demonstrate the advantages of these techniques in terms of survivability, reliability and peformance

* Conduct tradeoff studies in the areas of weight, volume, cost, maintainability, survivability and safety

* Derive design, performance, reliability, maintainability, test and application criteria

* Document the acquired knowledge for use in acquisition of future weapon systems

* Develop handling qualities criteria to allow full usage of modern control techniques for improvement in weapon system performance

Phase IIA - Fly-by-Wire with Emergency Mechanical Backup

As shown in Fig 7, reversion to the mechanical control system will be possible in the pitch and yaw axes only. The mechanical isolation mechanisms function as variable-gain devices with the mechanical system having zero gain when fly-by-wire is engaged. In all three axes, secondary actuators (either hydraulic or electro-mechanical) convert the four-channel electrical information into the physical motion required to operate the existing F-4 surface actuators.

The basic requirements for the fly-by-wire system are as follows:

a. Provide three-axis flight control through the entire performance envelope of the F-4 aircraft

b. Include C* (blended pitch rate and acceleration) or a similar longitudinal control/response mechanization

c. Include dispersed quadruple redundant electronics and sensors for a two-fail/operate capability. (Minimum performance degradation after two <u>like</u> failures.)

d. Provide superior control performance for precise weapons delivery and tracking

e. Include a simple direct electrical link which allows the pilot to command surface position. This open-loop system, containing a minimum of electronics, will serve as a separate emergency backup to the closed-loop fly-by-wire system.

f. Include redundant self-adaptive gain changing to maintain maximum performance capability in all flight conditions.

g. Include sidestick controllers in both pilot's stations appropriately synchronized, with pitch axis vernier capability.

h. Include cockpit failure monitoring and reset capability.

i. Include built-in test equipment (BITE) for go/no-go preflight check and fault isolation to a line replaceable unit.

j. Include a design reliability analysis with a system design goal failure rate of $\lambda = 2.3 \times 10^{-7}$.

k. Be capable of operation with the integrated servo actuator packages to be installed in Phase IIC.

l. Include interface capability with outer control loops such as autopilot, automatic landing systems, automatic terrain following, and direct lift control systems.

m. Include a selectable neutral speed stability capability.

Phase IIA work encompasses all of the criteria development and analyses required for specification and design of a production fly-by-wire system. It includes study and analysis of reliability, maintainability, survivability, nuclear hardening, lightning protection, control criteria, and electrical system requirements. Extensive computer simulations and control system mockup tests are planned, with actual hardware being tied into the simulations as it becomes available. Approximately 20 test flights are planned.

Phase IIB - Fly-by-Wire Flight Control System

As illustrated in Fig 7, Phase IIB aircraft modification consists essentially of removing the mechanical flight control system which was retained in Phase IIA as an emergency backup. Demonstration flights with pilots from Air Force, Navy, NASA, and/or other interested agencies are planned.

At this point, the advanced development program will have demonstrated the practicability and reliability of fly-by-wire flight control systems. The design methods, control criteria, and reliability data that will have been developed will provide sufficient background and confidence for inclusion of fly-by-wire flight control systems in production military and civil aircraft. Such aircraft will exhibit:

a. Vastly improved handling qualities and precision control capability.

b. Greatly reduced pilot workload through use of sidesticks.

c. Modest weight reductions through replacement of steel rods, pulleys, and cables by electric wires.

d. Reduced maintenance manhours through use of built-in test equipment.

e. Reduced maintenance downtime through use of line replaceable electronics units, which will be identical in the four redundant channels.

f. Improved flight control system reliability and safety through dispersion and redundancy.

g. Modest increase in survivability due to the dispersed, redundant control channels. This is in addition to the survivability improvements gained through use of the Simplex integrated actuator package.

h. Improved ride through gust alleviation (due to aircraft motion feedbacks).

In addition, availability of a proven fly-by-wire control system will make possible large weight reductions through a basic change in aircraft design philosophy. Work in this area is proposed in the "Controls Configured Vehicle" Advanced Development Program.

Phase IIC - Survivable Stabilator Actuator Package

As illustrated in Fig 7, Phase IIC consists of installing a Duplex Survivable Stabilator Actuator Package (SSAP) in the longitudinal axis. The Simplex IAP with built-in pump and motor is intended to provide emergency get-home-and-land capability upon loss of both aircraft central hydraulic systems. However, the IAP developed for Phase IIC will control the aircraft within the same flight envelope and performance capabilities as the present system. A single central hydraulic system will be plumbed to the SSAP for an additional degree of redundancy, but will only serve as a backup source.

The SSAP will contain logic and switching systems designed such that switching transients, steady-state errors, etc., are minimized and consistent with aircraft structural limits and normal pilot control capabilities. A monitor and control scheme will be devised such that the pilot can make the final decision in the event of component, power suppy, or pump-motor failure. The SSAP will be compatible with the fly-by-wire control system already installed in the aircraft.

Phase IIC will include study and analysis of the reliability, maintainability, and survivability of the redundant IAP's, plus computer simulations and "iron bird" control system mockup tests. Approximately 30 test flights are planned.

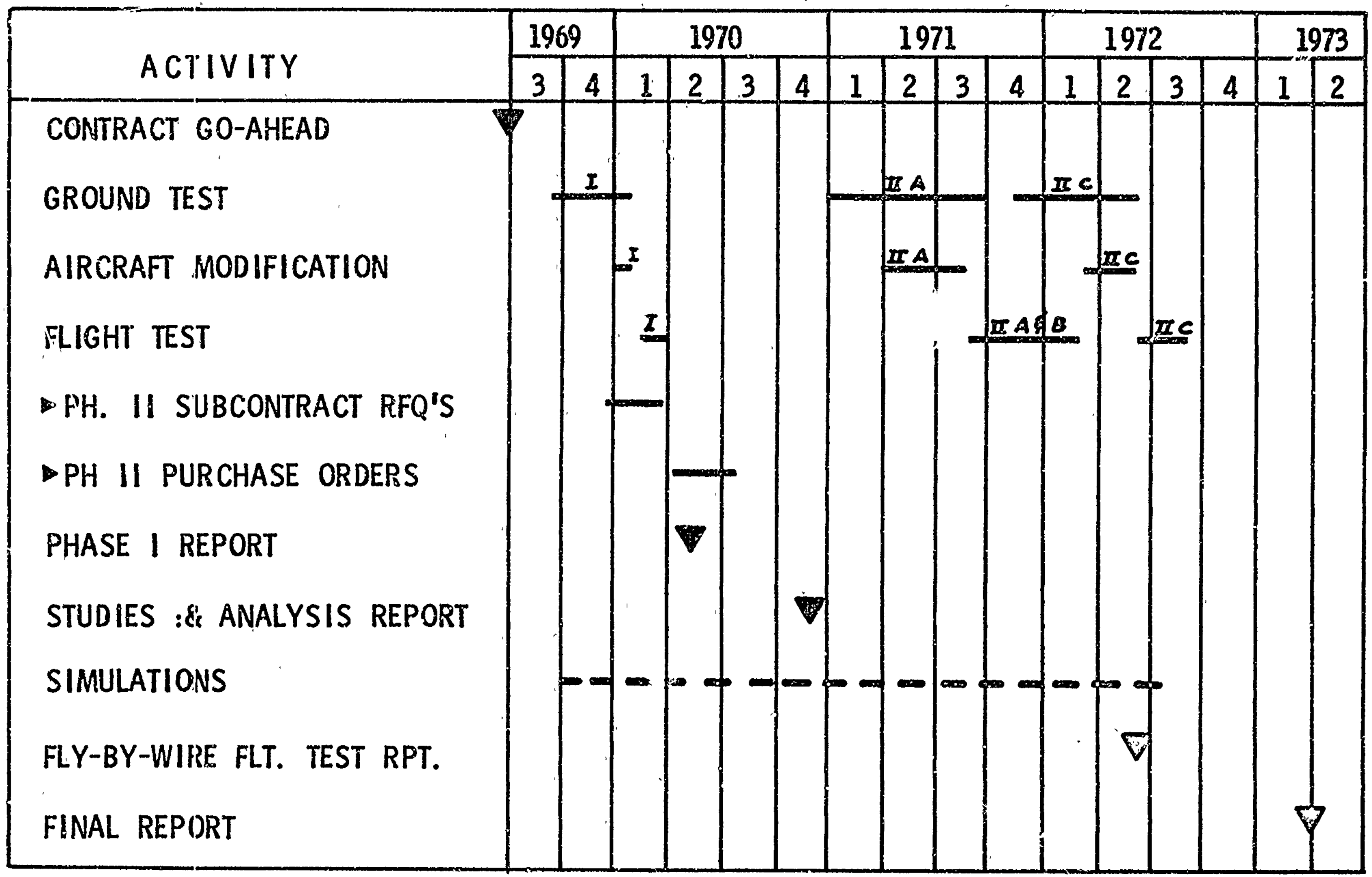
SCHEDULE

The SFCS Program schedule is shown in Fig 8.

SUMMARY

The combination of redundant integrated servo actuator packages and a redundant dispersed fly-by-wire flight control system will provide the ~~truly~~ survivable flight control system that is the goal of this advanced development program. Not only will aircraft survivability be improved in the face of a given quantity and quality of enemy fire. The improved handling qualities, precision control capability, and reduced pilot workload will combine to destroy a given target with given weapons with fewer passes through improved accuracy. Thus, exposure to hostile fire in performing a given task will be reduced, improving fleet, as well as individual aircraft survivability. The "Survivable Flight Control System" can make our future military aircraft less vulnerable, more efficient, more available, and consequently less expensive in terms of total cost of ownership.

FIGURE 8 - SURVIVABLE FLIGHT CONTROL SYSTEM SCHEDULE



▶ SFC ELECTRONICS SET, SECONDARY ACTUATORS, STABILATOR IAP, AND SIDESTICKS.

APPENDIX

The following reports cover important parts of the technology base for the Survivable Flight Control System Program as regards fly-by-wire techniques, integrated hydraulic servo-actuator packages, electrical and hydraulic redundancy techniques, and reliability and survivability predictions and assessment methods:

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